POWER PLANTS WITH AQUIFER THERMAL ENERGY STORAGE

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ABSTRACT

Energy demand variation for heating and cooling in twenty-four hours, wind generators, hydro-power stations and even nuclear energy lead to energy storage problems. The report is devoted to estimation of an energy accumulating power plant with a heat accumulator formed in the aquifer.
Energy accumulating by high temperature air is proposed in geologic conditions of Latvia, where there a large experience is collected with underground natural gas storages. The aim of the realised research was to calculate thermodynamic cycle of the power plant with 150 - 700 m deep aquifers in sandstones with a clay layer covering.
Experimental investigation of changes in composition and properties of sandstones with different cementation caused by high temperature air was made under high pressures and temperatures 650-800 ^{o}C, calculated as typical for the accumulators.

1. BACKGROUND

Power plants with aquifer thermal energy storage (ATES) can use high temperature air pumped into the underground geological structures by electrically supplied air compressor at the night minimum hours and under other conditions. In case of necessity during maximal consumption hours compressed air pressure potential energy is released and transformed back to electrical energy with the help of an air turbine and a turbo generator.

ATES power plants are foreseen as stabilization elements for high power electro energy grids to equal the uneven energy consumption graph during the day, storing the night excess and returning it back to the grid during the maximal consumption hours during the day. Completing this task the ATES power plant ensures the operation of main generating power of nuclear power plants and thermal power plants at their optimal conditions.

ATES power plant can work on the energy market as an independent member, buying cheap excess energy from the night minimum hours and under other conditions, and selling it during maximal consumption hours under a definitely higher price, as well as offering other services.

The type of air compression heat energy accumulation is not new and is offered in several international patents, for example, DE 2939631, US4403477, WO9601942, JP1110779, JP63208627, etc. as well as in the patent LV13216B of the Latvian inventor Egils Spalte, whose patent after the international classification belongs to F0206/14 and F02C6/16 classes.

The international patents offer to use air caves, caverns, etc. existing in natural solid rocks or artificial underground tanks. The volume of such tanks is limited, that logically limits the planned energy capacity and power of the air compression heat accumulated power plant. The main disadvantage of such underground tanks is that in case of the possibility of using the tanks as heat accumulators the losses might be rather high, because the solid rocks that form the walls of the tank transfer heat very well.

ATES can be created on the basis of a natural tank from 150 m up to 700 m deep. The construction features depend on the deepness of the layer suitable for the tank and the hydrostatic (inside) pressure that defines the power of the plant, as well as the construction of the gas turbine and the compressor. CAPP power plant after the operation pressure (that means that after the deepness of the tank) can be divided in two groups:

- ATES is located no deeper then 400 m and the compressor operates without air any agent – between section cooling, taking from the compressor on the last step all air with a high content of heat (not taking in account the losses) to the ATES,
- ATES is located deeper then 400 m and work with air between the section cooling process, between the section cooling heat accumulation and release from the cooling system, in time of the turbine cycle of heat regeneration. From the last section of the compressor only a part of air compression heat is transferred to the ATES.

The main criterion that defines the construction of the compressor is the maximal allowed temperature of the air, that must not be higher then the disintegration point of the underground rock material or the melting point of the material from which the equipment and units are made. It must be followed to ensure a longer working age of the machinery (up to 200-300 thousands of hours, and even more). The limit of the temperature is 500-550°C after the values of the heat-resistance of the mentioned materials.

In order to implement the idea of the ATES power station many tasks have to be performed, including theoretical and experimental research in the high temperature conditions of geophysical and mechanical properties of the rocks forming the underground heat accumulators.

The geological structures of Latvia are formed by sandstone of different composition and with different degree of cementation. It is cemented by clay - carbonate, gypsum or dolomite binding medium. Sandstone specimens of different composition have been chosen for the experiments and changes in the specimens have been investigated at increased temperature (650 – 800^{o}C).

2. CHARACTERISTICS OF SANDSTONE AS THE HEAT ACCUMULATING SUBSTANCE

Sandstones are rocks, where sand is cemented by a cementing substance. The bulk of Latvian sandstones are quite unconsolidated rocks, therefore, it is often difficult to decide what designation is more appropriate for the concerned rock – sand or sandstone. Sandstones found in other countries with the compressive resistance of 600 – 1500 kg/cm^2 appear for unconsolidated quartz and other rock grains cemented with silica or carbonates. In Latvia, hard sandstones (the compressive resistance of 150 – 570 kg/cm^2) appear only in some places, and their cementing substance is limestone or dolomite (the Rembate sandstone).

The Devonian sandstones contain fine quartz sand grains, which are slightly cemented with clay, iron hydroxide or calcium carbonate. There is a small amount of binding agents, therefore, such sandstones are not sufficiently hard (the Cesis – Valmiera sandstones).

The sandstones cemented with the clayey “cement” have the lowest mechanical strength. These sandstones also contain a small quantity of feldspar.

For experiments on sandstone changes at increased temperature, the Rembate and Devonian (Cesis-Valmiera) sandstones have been chosen.

Rembate sandstone

Average composition: dolomite – 58 %, quartz - 37 %, glauconite – 4 %, feldspar - 1%. Composition of sands is homogenous, with 0.1 – 0.2 mm large grains prevailing. The cementing substances are dolomite and glauconite. The colour is reddish, water absorption is 13 – 15 vol. %, and compressive strength is 150 – 570 kg /cm2.

Average chemical composition in %: SiO_2 - 20.5, CaO - 21.64, MgO - 15.84, Al_2O_3 - 4.8, Fe_2O_3 - 0.6, $Na_2O + K_2O$ - 0.26; ignition loss at 1,000^{o}C is 34.6 %.

Devonian sandstone

Unconsolidated rock of grey colour, slightly cemented with clay parts and calcium carbonate. It contains fine sand grains of 0.1 – 0.5 mm.

It consists almost entirely of quartz, with the negligible addition of illite and feldspar.

Chemical composition: SiO_2 (+Al_2O_3 + Fe_2O_3) - 81.85 %, $CaCO_3$ - 18.15 %, ignition loss at 800 ^{O}C is 5.84 % (≈ 10 % $CaCO_3$).

3. EXPERIMENTAL PART

In order to determine impact of the increased temperature at the researched sandstones, the following tests have been made:

- thermal processing of the specimens has been performed at the temperatures of 600, 700 and 800^{0}C for 1.5 hours;
- density and water absorption have been determined for the obtained specimens;
- thermal analysis of the specimens has been performed on the MOM Paulig & Paulig derivatograph;
- X-radiographic researches of the thermally unprocessed and heated specimens have been performed on the Rigaku Ultima equipment + X-ray diffraction meter.

The sandstone thermal processing data (Table 1) demonstrate that up to the temperature of 600^{o}C no significant changes take place in the material. Starting with 700^{o}C, the sandstone density is decreasing, water absorption is increasing and ignition loss is growing, but at the temperature of 800^{o}C the material decomposes.

Table 1

Impact of thermal processing on the sandstone density and water absorption

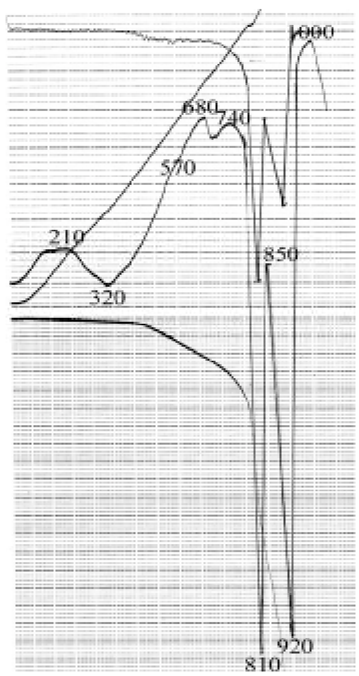
Specimen	Therm. proc. temperat., ^{o}C	Density, g/cm^3	Water absorption, %	Notes
Rembate s/s	w/o process.	2.46	3.1	
Rembate s/s	700^{o}C	2.21	7.8	weight loss 8.6%
Cesis-Valm. s/s	w/o process.	2.39	3.6	
Cesis-Valm. s/s	600^{o}C	2.39	3.9	
Cesis-Valm. s/s	700^{o}C	2.24	6.0	weight loss 5.8%
Cesis-Valm. s/s	800^{o}C	-	-	the specimen decomposes

These changes of the sandstone properties can be explained by the thermal analysis and radiographic researches.

Calcite ($CaCO_3$) disassociates at the temperature of 800 – 1000^oC, forming CaO and CO_2. The disassociation temperature depends on the thermal processing parameters (the temperature increase rate, duration of thermal processing, pressure, etc.), as well as of $CaCO_3$ quantitative amount in the rock. In case of a small amount of $CaCO_3$, its disassociation starts from 720^oC.

Dolomite $CaMg(CO_3)_2$ decomposes and disassociates within the temperature interval of 720 – 870^oC. Decomposition of dolomite also depends on the type of thermal processing. Dolomite initially decomposes into $CaCO_3$ and $MgCO_3$; disassociation of magnesite takes place at 580 – 680^oC. Products of dolomite decomposition are carbon dioxide and mixture of calcium and magnum oxides. Reaction of these oxides with quartz is possible at a relatively low temperature (700 – 850^oC), forming calcium silicates.

Quartz SiO_2 – the main constituent part of sandstone - is thermostable; at the temperature of 573^oC polymorphic transformation from the low temperature to the high temperature quartz takes place, but it does not impact the sandstone thermal processes.



The Rembate sandstone derivatogram is shown on Figure 1. The endoeffect at 210-400^oC is due to discharge of moisture from the specimen; a slight endoeffect at 570^oC is due to change of quartz modifications. At the temperature of 740 – 850^oC, decomposition of $MgCO_3$ takes place, and then, with the maximum at 920^oC, decomposition of $CaCO_3$.

Figure 1. Derivatogram of the Rembate sandstone

The Rembate sandstone roentgenograms (Fig. 2) show that the material consists mostly of quartz and dolomite, which is the binding agent in this sandstone. At the temperature over 650^oC, decomposition of dolomite starts, at 700^oC it is still partially retained, thus, the sandstone has not yet fully decomposed, though its density is reduced (by ≈ 10 %) and water absorption increases (Table 1).

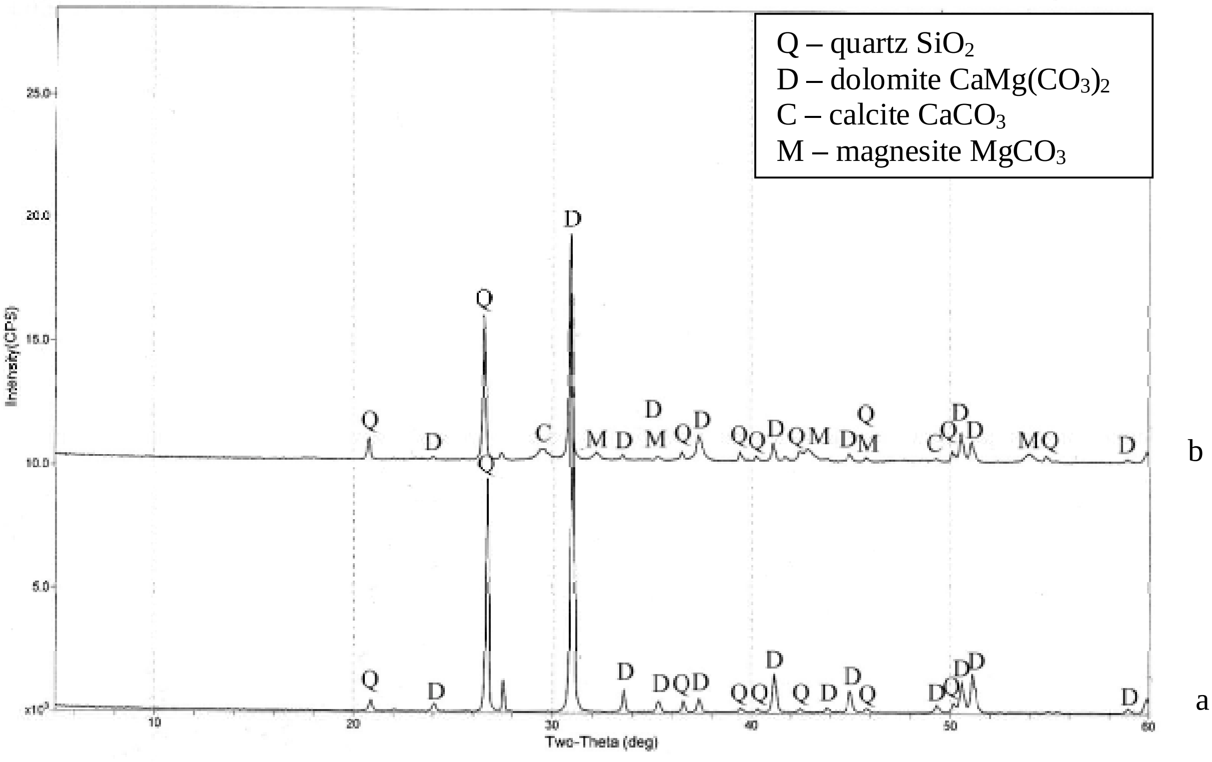
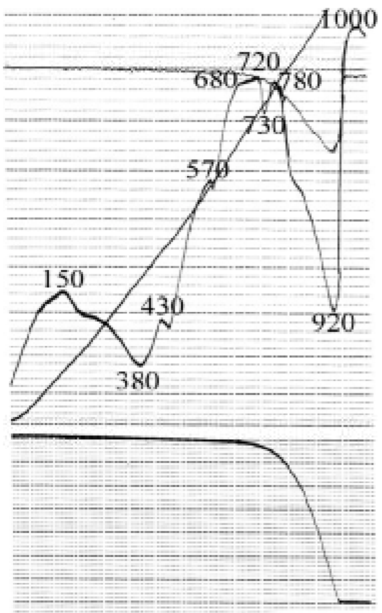


Figure 2. The Rembate sandstone roentgenogram: a – thermally unprocessed; b – thermally processed at 700^{0}C.



At the Cesis-Valmiera region sandstone derivatogram (Fig.3), the endoeffects at 150 – 430^{o}C, with the maximum of 380^{o}C, are due to discharge of moisture from the specimen, but at 680 – 780^{o}C due to decomposition of clay minerals. The large and fast endoeffect and considerable weight losses at 780–1000^{o}C pertain to decomposition of calcite.

Figure 3. Derivatogram of the Cesis-Valmiera region sandstone

Analysis of X-ray phases (Fig.4) shows that the Cesis-Valmiera sandstone consists of quartz, which is cemented with calcite and a small quantity of clay. At 600°C, clay minerals decompose in the specimen; however, cementation with $CaCO_3$ is still retained. The amount of the latter is reducing fast at 700°C, but at 800°C calcite has already mostly decomposed and the sandstone has disassociated.

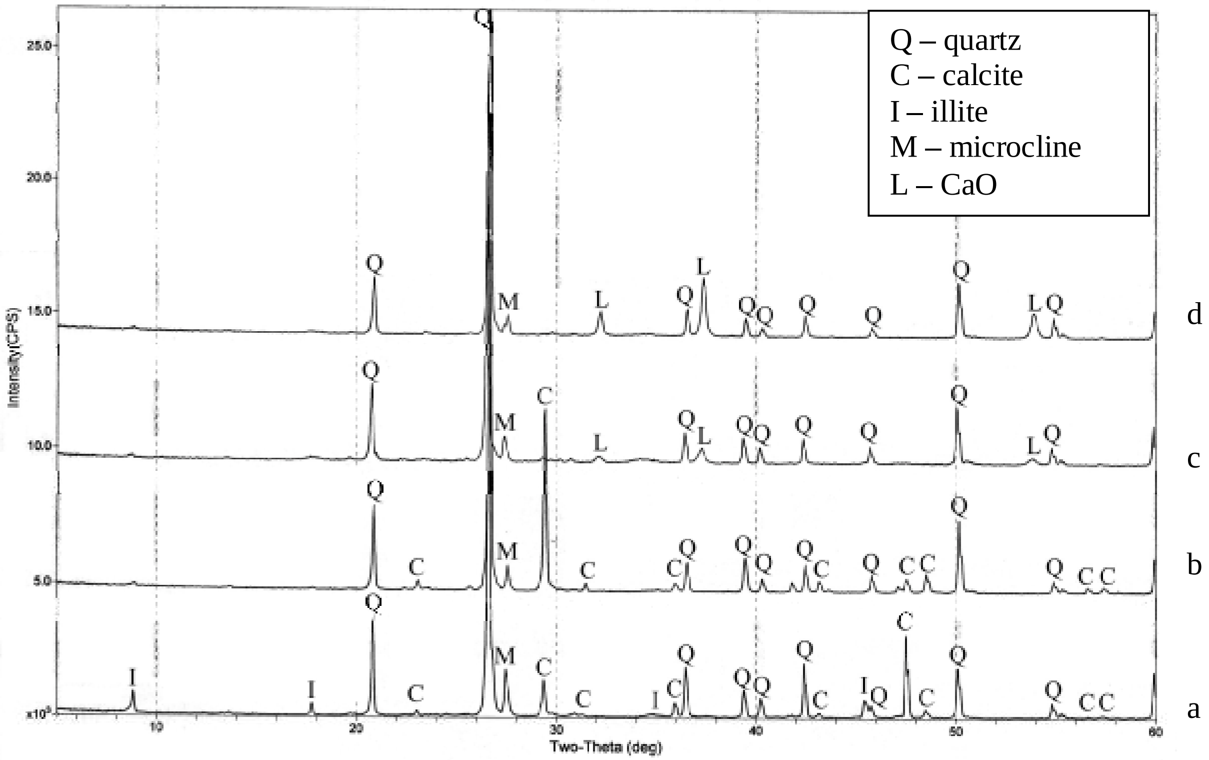


Figure 4. Roentgenograms of the Cesis-Valmiera region sandstone, depending on its thermal processing: a – unprocessed, b – processed at 600°C, c – processed at 700°C, d – processed at 800°C.

4. CONCLUSIONS

1. Under the impact of temperature up to 600°C, sandstones retain their composition and properties. At higher temperatures (over 600 – 650°C), gradual decomposition of the cementing minerals and disassociation of sandstone starts. As a result, density of the material decreases, its porosity decreases and strength reduces. At 800°C sandstone disassociates, respectively transforming into sand.
2. During implementation of the ATES power plant idea, the hot air temperature of 600°C can cause problems (too high).